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DOI:

[10.1177/0361198120982310](https://doi.org/10.1177/0361198120982310)

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Document Version

Peer reviewed version

Citation for published version (Harvard):

Usman, K, Burrow, M, Ghataora, G & Sasidharan, M 2021, 'Using probabilistic fault tree analysis and monte carlo simulation to examine the likelihood of risks associated with ballasted railway drainage failure', *Transportation Research Record*, no. 6, pp. 70-89. <https://doi.org/10.1177/0361198120982310>

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Using Probabilistic Fault Tree Analysis and Monte Carlo Simulation to Examine the Likelihood of Risks Associated with Ballasted Railway Drainage Failure

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Word Count: 7558 words + 3 tables (250 words per table) = 8308 words

Submitted [08/07/2020]

ABSTRACT

Inadequate track drainage can lead to a variety of issues, including flooding, accelerated track degradation and progressive or sudden railway track, slope or embankment failure. These can result in unplanned track maintenance, additional passenger travel costs and damage to third party property. However, railway drainage asset management is challenging because it involves the consideration of large interconnected assets, limited maintenance budgets, and unknown failure probabilities. To address this issue, this paper introduces a risk-informed approach for railway drainage asset management that uses fault tree analysis to identify the factors that contribute to railway drainage flood risk and quantifies the likelihood of the occurrence of these factors using Monte Carlo simulation. This rational approach enables drainage asset managers to evaluate easily the factors that affect the likelihood of railway track drainage failure, thereby facilitating the prioritisation of appropriate mitigation measures and in so doing improve the allocation of scarce maintenance resources. The analysis identified 46 basic and 49 intermediate contributing factors associated with drainage failure of ballasted railway track (undesired event). The usefulness of the approach is demonstrated for three sites on the UK railway network namely, Ardsley Tunnel, Clay Cross Tunnel and Draycott. The analysis shows that the Clay Cross Tunnel had the highest probability of drainage failure and should be prioritised for maintenance over the other two sites. The maintenance required should focus on blockages due to vegetation overgrowth or debris accumulation.

Keywords: Railway drainage failure; Fault tree analysis (FTA); Monte Carlo simulation (MCS); Risk analysis; Asset management

1 INTRODUCTION

2 Proper railway track drainage is critical to the performance of any ballasted railway since it directly
3 impacts the railway track structure (28). Inadequate track drainage can lead to a variety of issues,
4 including flooding, accelerated track degradation and progressive or sudden railway track, slope or
5 embankment failure. These issues in turn can result in unplanned track maintenance and the imposition
6 of speed restrictions and delay times, additional passenger travel cost, damage to third party property
7 and farming land (51,55). Travel delay costs in the UK due to railway drainage failure alone amounted
8 to £119 m during the period 2000 – 2017 (39). Despite the potential costly impacts of inadequate railway
9 drainage, managing the maintenance of drainage assets is still often undervalued, in part because it is
10 not considered to be important or difficult to achieve.

11
12 However, railway drainage asset management is challenging because it involves the consideration of
13 large interconnected networks of assets, significant parts of which are buried and therefore difficult to
14 assess. These assets are made from a variety of materials which deteriorate at different rates, are of
15 varying ages and unknown maintenance history. In addition, the railway operational environment
16 constraints maintenance activities spatially and temporarily, maintenance budgets are often limited, and
17 the impact of drainage failure varies significantly across the railway network. This is exacerbated in
18 many countries which have ageing railway networks where the track and its drainage assets can be 150
19 years old and are nearing the end of their useful life necessitating increased rates of expenditure (16).
20 In the UK for example, it is estimated that the cost of drainage renewals doubled from £184/m in 2014
21 to £368/m in 2016 (51). A risk-informed approach to railway drainage asset management is therefore
22 required that allows the uncertainties associated with the extent and performance of assets and the
23 adverse impacts of their failure to be considered. Such an approach provides a rational and transparent
24 means for arguing for maintenance budgets and prioritising expenditure.

25
26 Various studies advocate the use of risk management to inform decision making in the railway industry,
27 typically to identify potentially harmful events and quantify their frequency of occurrence and impact.
28 Such studies include those associated with safety and the degradation of the track infrastructure. For
29 example, derailment (30) and failure of rolling stock (2); the safe operation of infrastructure including
30 tunnels (8), level crossings (9) and signals (59); security threats ranging from vandalism to terrorism
31 (20,49); the impact of ballast fouling on drainage performance (53), earthwork failure (14,41), and
32 infrastructure maintenance (12, 60). Several other studies focus on the effect of outside agents (weather,
33 flooding, landslides and earthquakes). For example, flooding risk and its impacts on the operation of
34 conventional rail in the UK (32,46), the weather on urban rail transit facilities in Beijing (31), track
35 disruption due to landslides (27) and earthquakes (47). Risk-informed approaches to deal with economic
36 impacts have been proposed, including cost overruns and demand shortfalls in urban rail (22) and
37 investment appraisal (19). There is however a paucity of research on railway drainage risk.

38
39 In the highways sector, drainage risk-informed studies are more prevalent. Barnet (7) developed an
40 approach informed by expert opinion to identify and quantify the risks of highway drainage flooding
41 and Kalantari and Folkson (25) investigated the potential causes and impacts of extreme weather
42 events on Sweden's national road network. Because of its potential severe impacts, the flood risk of
43 urban drainage has been studied extensively and indeed risk assessment forms an integral component
44 of the ASCE Standard Guidelines for the Design, Installation, and Operation and Maintenance of Urban
45 Subsurface Drainage (3).

46 In this regard, Coulthard and Frostick (13) formulated an approach based on spatial map analysis, taking
47 into account the performance of pumping stations and sewer networks to investigate the causes of
48 flooding in the UK city of Hull. Veldhuis *et al.* (57) proposed an integrated fault tree analysis-Monte
49 Carlo simulation model to identify and quantify the major factors contributing to urban flooding based
50 on reports from public call-centre and demonstrated their approach for Haarlem in the Netherlands.
51 Risk-informed approaches have also been used to model the deterioration of urban drainage assets,
52 stormwater pipes and sewers (1,5,49,54) and for managing urban flood risk (6,26,32,33).

To address the need for a risk-informed approach to help to identify sections of railway track at greatest flood risk and therefore prioritise investment to mitigate risk, this paper describes an approach to quantify the probability of drainage associated failure events at different locations in a railway network. In the approach, fault tree analysis (FTA) analysis is used to identify and estimate the probability of occurrence of the factors which contribute to drainage failure and takes into account uncertainty using Monte Carlo Simulation (MCS). The usefulness of this approach is demonstrated using three case studies of the UK's railway network. Compared to previous work presented in the literature the proposed approach contributes to the following:

- A risk-informed approach, that combines the use of FTA and MCS, to enable the probability of occurrence of railway drainage asset failure to be quantified.
- A fault tree that identifies the causal factors that could lead to railway track drainage failure.
- A conceptual framework that integrates drainage risk management within asset management.

ASSET AND RISK MANAGEMENT

Railway infrastructure asset management is a systematic, coordinated set of activities and practices that are carried out by an organisation to ensure the optimal performance of assets, at minimal risk, for a given budget to satisfy the organisation's strategic plan (10). It can be considered to operate at strategic, tactical, and operational levels of decision making (34). At the strategic level of management, the organisation's vision and mission are expressed in the corporate plan as part of strategic planning activities, and asset management framework is set, levels of service are aligned with strategic objectives, performance targets are agreed and the context for risk management established. Tactical level management concerns implementing the asset management framework and translating vision and mission statements to objectives and performance indicators. Operational management, on the other hand, is associated with defining standards and intervention levels of infrastructure asset condition. Strategies are developed to assess asset condition and thereafter implement works programmes (17)

Railway organisations are required to understand and manage a variety of risks at each management level to enable effective asset management. The potential impacts of these risks can be used to support asset management by informing the organisation's decisions regarding performance, investment and implementation of works programmes. Figure 1 summarises the three levels of asset management in terms of their relationship to an organisation's policy, strategy and management activities and shows conceptually how risk management can support the asset management process at each of the three management levels (17). **The policies define what the railway authority is aiming to achieve and are usually governed by stakeholder expectations, performance indicators and other targets. Strategy defines the mechanisms by which these policies are implemented and designates responsibilities within the railway authority. This is usually set out in corporate, business and operational plans, and is directly related to the three asset management levels. This translates into short-, medium- and long-term operational decisions ranging from managing an asset component to the whole railway network while identifying critical assets and risks associated with the operational activities.**

Data Requirements

The World Bank concept of information quality levels (IQL) has been used in this research to suggest the data requirements for different levels of railway asset management activity shown in Figure 1 (44). The IQL concept acknowledges that different qualities of data are required for these levels and it provides a standard for acquiring and using data when carrying out any management activity. This enables a sufficient amount and quality of data to be collected for the task in hand, thereby reducing unnecessary data collection and processing costs (48).

RISK

Risk identification, evaluation and mitigation can be considered as (34):

- Asset related (loss or damage)
- Contractual

- Environmental
- Financial
- Operational
- Reputational
- Safety
- Service-related (reduction or failure)

Formally risk, R , is evaluated through a combination of the probability of an event occurring and its consequence or impact, I , as defined by Equation 1 (24).

$$R = P \times I \quad (1)$$

In the context of railway drainage risk assessment, P is taken as the probability of flooding occurring and I is the impact of the flood event measured in terms of the eight above categories.

This paper focuses on an approach to identify and determine the probabilities, of the underlying factors which can cause a railway drainage failure event.

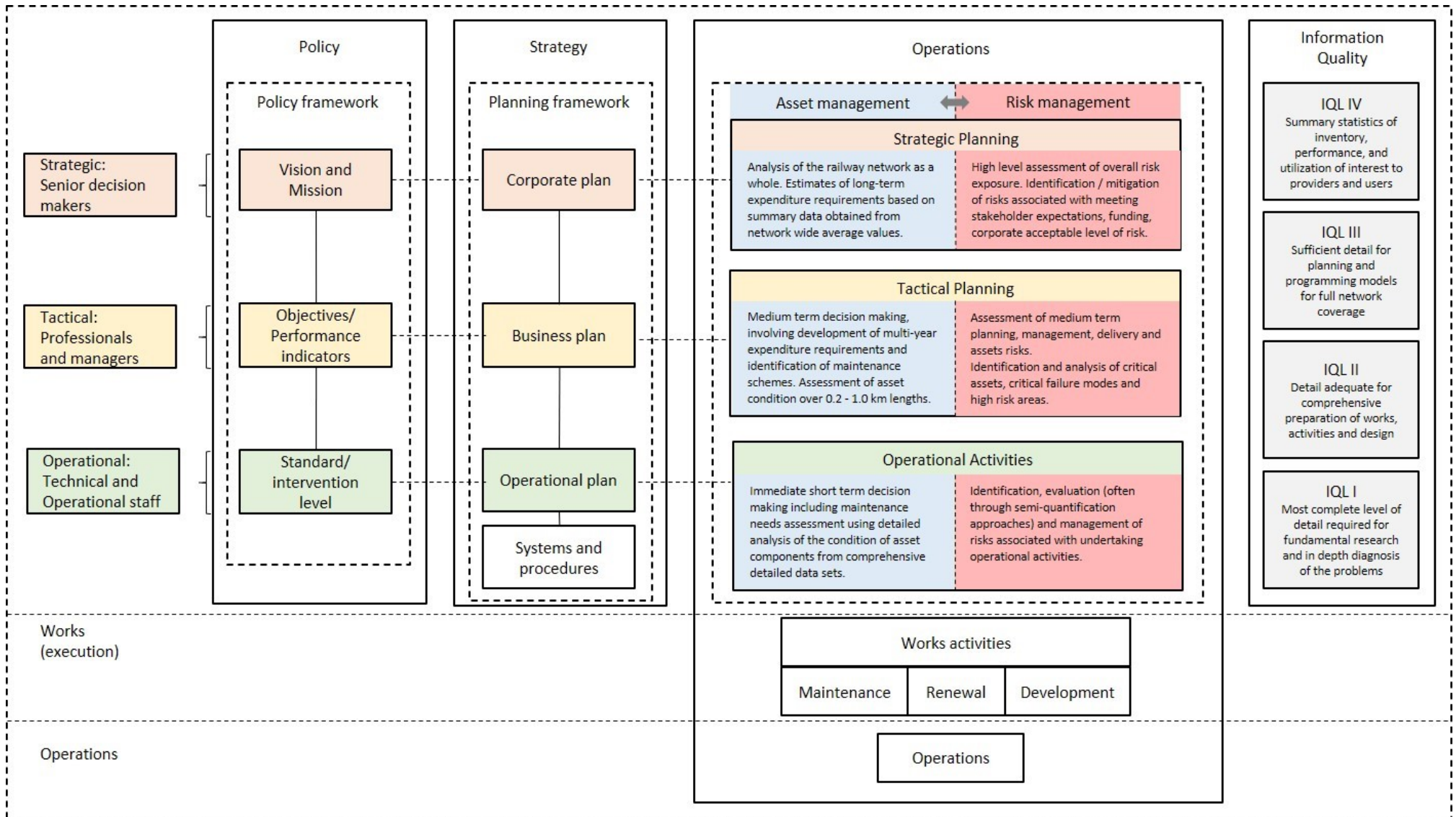


Figure 1 Railway asset and risk management framework (adapted from Robinson *et al.* [48])

THE PROPOSED FTA-MCS APPROACH

The approach proposed herein for estimating the probability of drainage failure of ballasted railway track (i) uses FTA to identify the factors that contribute to the failure of surface (i.e. pipes, catchpits and manholes) and subsurface (i.e. channel drains, ditches, outfalls and culverts) railway drainage assets, (ii) quantifies the probability of occurrence of these contributing factors (iii) takes into account the uncertainty of the information to estimate, using MCS, plausible ranges of the probability of occurrence values for each contributing factor. The approach is summarised in Figure 2 and is further described and justified below.

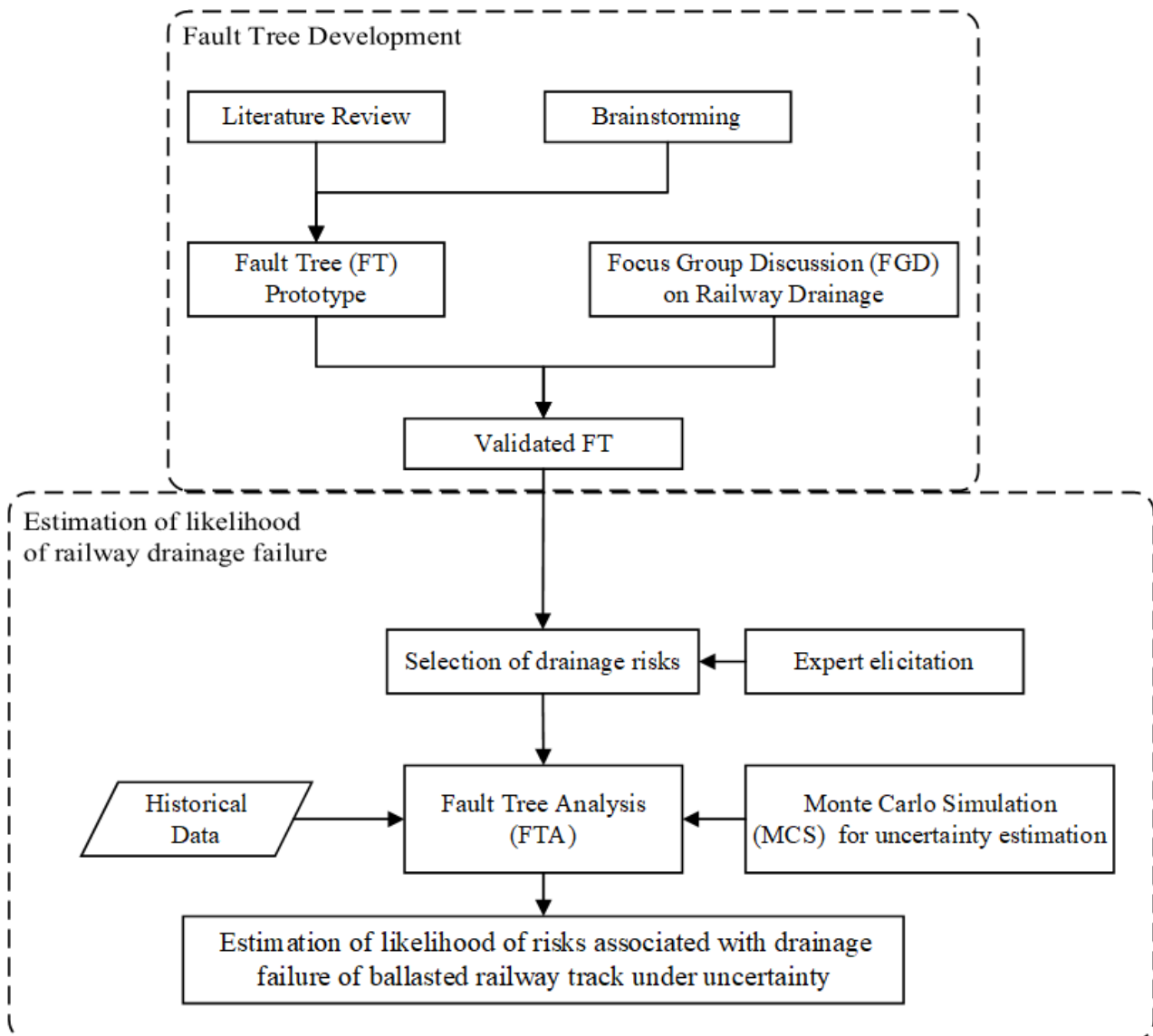


Figure 2 Flow chart of FTA-MCS approach to estimate the probability of drainage failure

Fault Tree Analysis

Fault tree analysis (FTA) is widely used in reliability analysis to help to identify potential causes of the failure of systems and it has been used for similar applications to railway track drainage (31,57). Furthermore, FTA enables the probability of the failure to be determined quantitatively from an analysis of the causal events and contributing factors (45,57). An added attraction of such an approach is that an appropriately developed FTA can be used as a diagnostic tool to identify and correct the causes of

1 failure. An FTA approach was therefore selected to identify and quantify the causal events and factors
2 contributing to railway drainage failure.

3 4 *Fault Tree Development*

5 FTA is a deductive approach whereby a failure is decomposed into its associated contributing factors
6 using a logic diagram known as a fault tree (FT) (e.g. see Figure 3) (31,45). For our work, the top event
7 of the fault tree was defined as drainage failure.

8
9 The review of the literature identified four categories of railway track drainage failure associated with
10 the five predominant railway drainage asset types as shown in Table 2. Thereafter the information
11 available in the literature together with brainstorming carried out with the aid of a contributing factors
12 diagram was used to identify the potential causal factors for each failure mode. The contributing factors
13 were separated into basic (i.e., that which has no contributing factor), and intermediate level factors
14 (29) using a combination of information available in the literature and via a workshop. The workshop
15 was attended by seven railway drainage and risk experts from Network Rail (NR), the UK's railway
16 infrastructure owner, and the authors. A total of 46 basic and 50 intermediate contributing factors were
17 identified and assembled into eight categories, namely environment, subgrade, design, component
18 (material) deterioration, installation, maintenance, and traffic (see Table 3). These contributing factors
19 were related using Boolean Algebra/logic gates to form a typical fault tree as presented in Figures 3-4.

20
21 It was assumed that the likelihood of occurrence of the contributing factors can be modelled using a
22 Poisson process and that the basic events act independently. This suggests that the events will occur in
23 any specified short period of time and will be approximately proportional to the length of that time
24 period. Similar assumptions were made by Veldhuis *et al.* (57) in a failure probability model for urban
25 drainage system using FT. Veldhuis *et al.* (57) postulated that the system, including all its various
26 components (e.g. pipes, basins, surfaces infiltration capacity), returned to their initial states between
27 two events (e.g.. successive floods).

TABLE 1 Failure Modes of railway drainage components adapted from NR (35)

No	Failure Mode	Affected Track Drainage Components					Condition and Indicators	Potential Causes
		Subsurface		Surface				
		C1	C2	C3	C4	C5		
1	Blocked	●	●	●	●	●	The capacity of the drainage component is reduced below a specified level.	Silting, poor alignment, vegetation/ root intrusion, debris infiltration (C1).
	Fully blocked	√	√	√	√	√	Capacity is reduced to zero.	Missing or ineffective covers, lack of silt trap (C2). Bank erosion and collapse, overgrown vegetation, frequent siltation and ponding (C3).
	Partially blocked	√	√	√	√	√	For C1, C2, C3, and C4 : 25%<capacity<50%. For C5, capacity<50%.	Seized flap valve (C4). Silting, debris infiltration (C5).
2	Collapsed	●	●	●	●	●	The drainage component is not fuctioned properly.	Material corrosion, damage by ground movement, by track plant (i.e. track vehicles), train induced dynamic loads (C1, C2).
	Completely collapse	√	√	√	√	√	A structural failure occurs on more than one pipe (C1) length or the most parts of the structure (for C2,C3,C4, and C5).	Bank instability, the removal of vegetation, scour, burrowing animals (C3).
	Partially collapsed	√	√	√	√	√	A major part of the pipe has cracked or deformed but the collapse is less than one pipe (C1) length or missing some parts (for C2, C3, C4, and C5).	General deterioration, scour (C4, C5).
3	Filter Media Clogged	●	X	X	X	X	Geotextile layer as filter media inhibits water entering the pipe (C1) resulting water to remain on track surface or saturates the ground.	Clogged through the accumulation of fines on the surface of geotextile layer (C1).
4	Indequate Capacity	●	●	●	●	●	The components (C1, C2, C3, C4, and C5) are being overwhelmed by the flow of water, even they are in good working order (hydraulic surcharging).	Change of gradient due to subgrade settlement, the disturbance of formation, inadequate pipe capacity for the size of catchment runoff, and insufficient depth of catchpits and manholes (C1, C2).
								Inadequate gradient, inadequate pipe capacity for the catchment, accelerated runoff due to land use change within the catchment area, changes to upstream drainage condition, and extreme weather events (C3, C5).
								Inadequate capacity issue associated with the outfall are as those above, albeit an inadequate gradient is less of an issue (C4).

C1: Pipes; C2: Catchpits and Manholes; C3: Channel Drains and Ditches; C4: Outfalls; C5: Culverts

TABLE 3a Causal factors (i.e. basic, intermediate) and their contributing factors associated with drainage failure of ballasted railway track (top event)

Code	Causal Event (Risk)	Type	Contributing Factor	Code	Causal Event (Risk)	Type	Contributing Factor
X1	Poor filter	BE	Design	X22	Lack of silt trap	BE	Design
X2	Root (tree) penetration	BE	Environmental	X23	Aging catchpits and manholes	BE	Component
X3	Train dead load (track vehicles) overloading.	BE	Traffic	X24	Insufficient depth catchpits and manholes	BE	Design
X4	Train live load (dynamic load, speed) overloading.	BE	Traffic	X25	Vegetation overgrowth	BE	Maintenance
X5	Weak soil	BE	Subgrade	X26	Spoil tipping	BE	Maintenance
X6	Flooding from surface water (heavy rainfall)	BE	Environmental	X27	Defective trash screen	BE	Maintenance
X7a	Flooding from rivers	BE	Environmental	X28	Aging channel drains and ditches material	BE	Component
X7b	Flooding from sea	BE	Environmental	X29	Scour around channel drains and ditches	BE	Environmental
X7c	Flooding from reservoirs	BE	Environmental	X30	Inadequate gradient of channel drains and ditches	BE	Design
X8	Excessive soil pressure	BE	Subgrade	X31	Seized flap valve	BE	Component
X9	Aging pipes	BE	Component	X32	Scour around headwall, apron and cascade	BE	Environmental
X10	Weathering (chemical)	BE	Environmental	X33	Structural defect on headwall, apron and cascade	BE	Component
X11	Changes to land use (catchment area)	BE	Land use	X34	Aging outfalls material	BE	Component
X12	Changes to upstream drainage condition	BE	Land use	X35	Structural defect of culverts	BE	Component
X13	Inadequate pipe gradient	BE	Design	X36	Sour of culverts (inlet or outlet)	BE	Environmental
X14	Inappropriate design of granular filter	BE	Design	X37	Aging culverts material	BE	Component
X15	Fines accumulation from trenches surround pipe	BE	Maintenance	X38	Inadequate culverts gradient	BE	Design
X16	Fines accumulation from pipe(s) surround drain	BE	Maintenance	X39	Inadequate design (i.e. inadequate data, inappropriate product selection)	BE	Design
X17	Inappropriate design of geotextile filter	BE	Design	X40	Damage caused by other assets/ 3rd party assets	BE	Land Use
X18	Scour of pipes	BE	Environmental	X41	Damage caused by burrowing animals	BE	Maintenance
X19	Lack of debris clean out	BE	Maintenance	X42	Damage caused by lack of structural maintenance	BE	Maintenance
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	BE	Maintenance	X43	Damage caused by poor installation	BE	Installation
X21	Poor ballasting practices	BE	Maintenance	X44	Prolong extreme hot wetaher	BE	Environmental

TABLE 3b Causal factors (i.e. basic, intermediate) and their contributing factors associated with drainage failure of ballasted railway track (top event) (continue)

Code	Causal Event (Risk)	Type	Contributing Factor	Code	Causal Event (Risk)	Type	Contributing Factor
H1	Excessive water infiltration to track bed	IE	Environmental	D1	Blocked pipes	IE	Pipes failure
H2	Excessive shrinkage below drain level due to moisture	IE	Environmental	D2	Collapsed pipes	IE	Pipes failure
G1	Softening below drain level	IE	Subgrade	D3	Inadequate capacity of pipes	IE	Pipes failure
F1	Settlement (change of gradient)	IE	Subgrade	D4	Filter media problem of surrounding pipes	IE	Pipes failure
F2	Cess heave	IE	Subgrade	D5	Blocked catchpits and manholes	IE	Catchpits and manholes failure
F3	Fines accumulation from surround pipes	IE	Maintenance	D6	Collapsed catchpits and manholes	IE	Catchpits and manholes failure
F4	Erosion	IE	Environmental	D7	Inadequate capacity of catchpits and manholes	IE	Catchpits and manholes failure
F5	Damaged or missing covers of catchpits and manholes	IE	Maintenance	D8	Blocked channel drains and ditches	IE	Channel drains and ditches failure
E1	Silting pipes	IE	Maintenance	D9	Collapsed channel drains and ditches	IE	Channel drains and ditches failure
E2	Ground movement	IE	Subgrade	D10	Inadequate capacity of channel drains and ditches	IE	Channel drains and ditches failure
E3	Overstress	IE	Traffic	D11	Blocked outfalls	IE	Outfall failures
E4	Deterioration of pipes material	IE	Component	D12	Collapsed outfalls	IE	Outfall failures
E5	Granular clogged (i.e. collector, carrier, french/land drain)	IE	Design	D13	Inadequate capacity of outfalls	IE	Outfall failures
E6	Geotextile clogged (i.e. collector, carrier drain)	IE	Design	D14	Blocked culverts	IE	Culverts failure
E7	Catchpits and manholes blocked by debris	IE	Maintenance	D15	Collapsed culverts	IE	Culverts failure
E8	Chambers filled or buried with material	IE	Maintenance	D16	Inadequate capacity of culverts	IE	Culverts failure
E9	Silting catchpits and manholes	IE	Maintenance	C1	Defective or failed pipes	IE	Pipes failure
E10	Deterioration of catchpits and manholes material	IE	Component	C2	Defective or failed catchpits and manholes	IE	Catchpits and manholes failure
E11	Bank instability	IE	Subgrade	C3	Defective or failed channel drains and ditches	IE	Channel drains and ditches failure
E12	Silting channel drain and ditches	IE	Maintenance	C4	Defective or failed outfalls	IE	Outfalls failure
E13	Deterioration of channel drains and ditches material	IE	Component	C5	Defective or failed culverts	IE	Culverts failure
E14	Silting outfall	IE	Maintenance	B1	Defective or failed subsurface track drainage	IE	Subsurface track drainage failure
E15	Deterioration of outfall material	IE	Component	B2	Defective or failed surface track drainage	IE	Surface track drainage failure
E16	Silting culverts	IE	Maintenance	Code	Undesired Event (Risk)	Type	Failure Mode

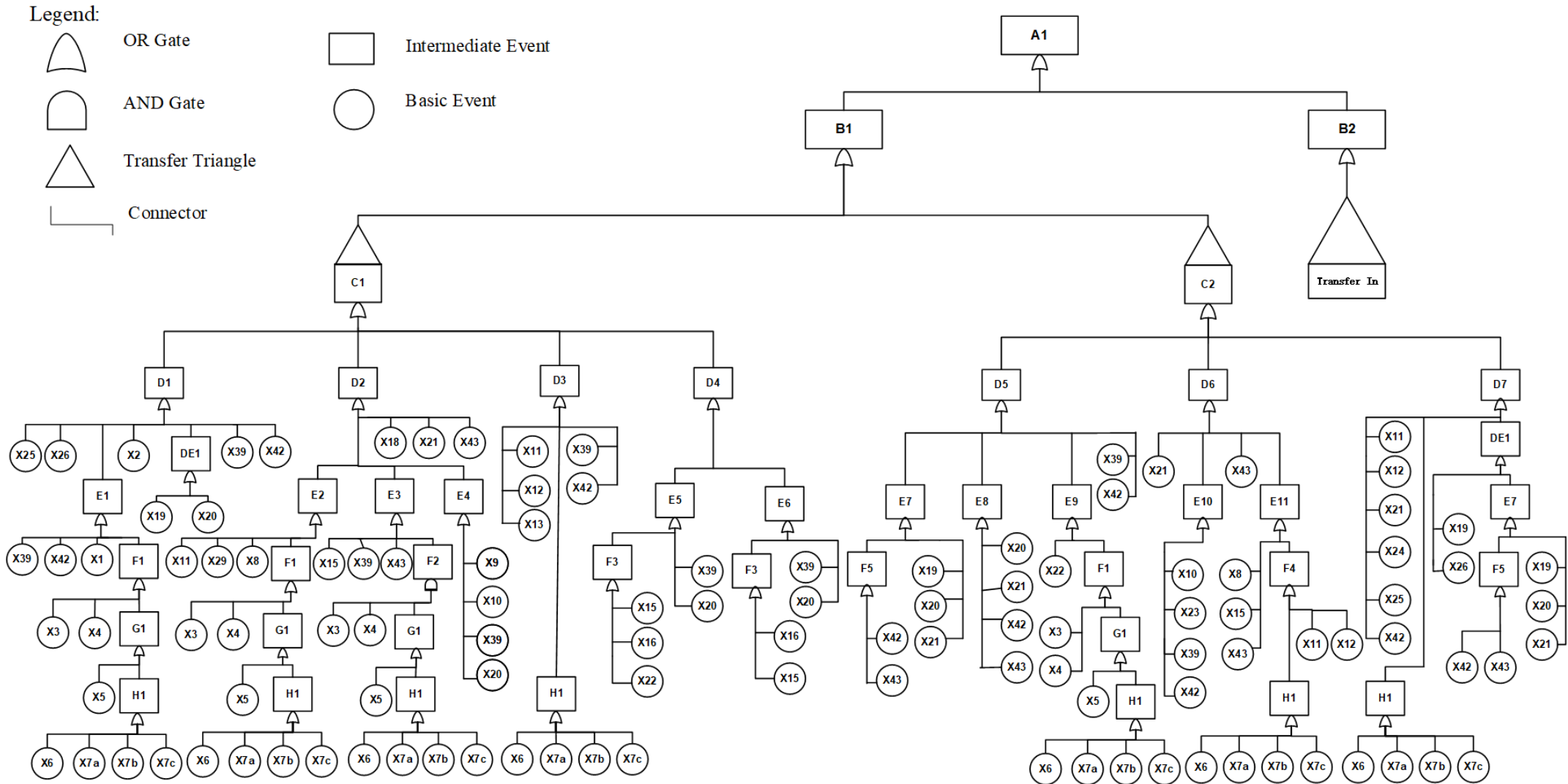


Figure 3. Railway drainage FT and sub-FT for C₁ and C₂ drainage assets

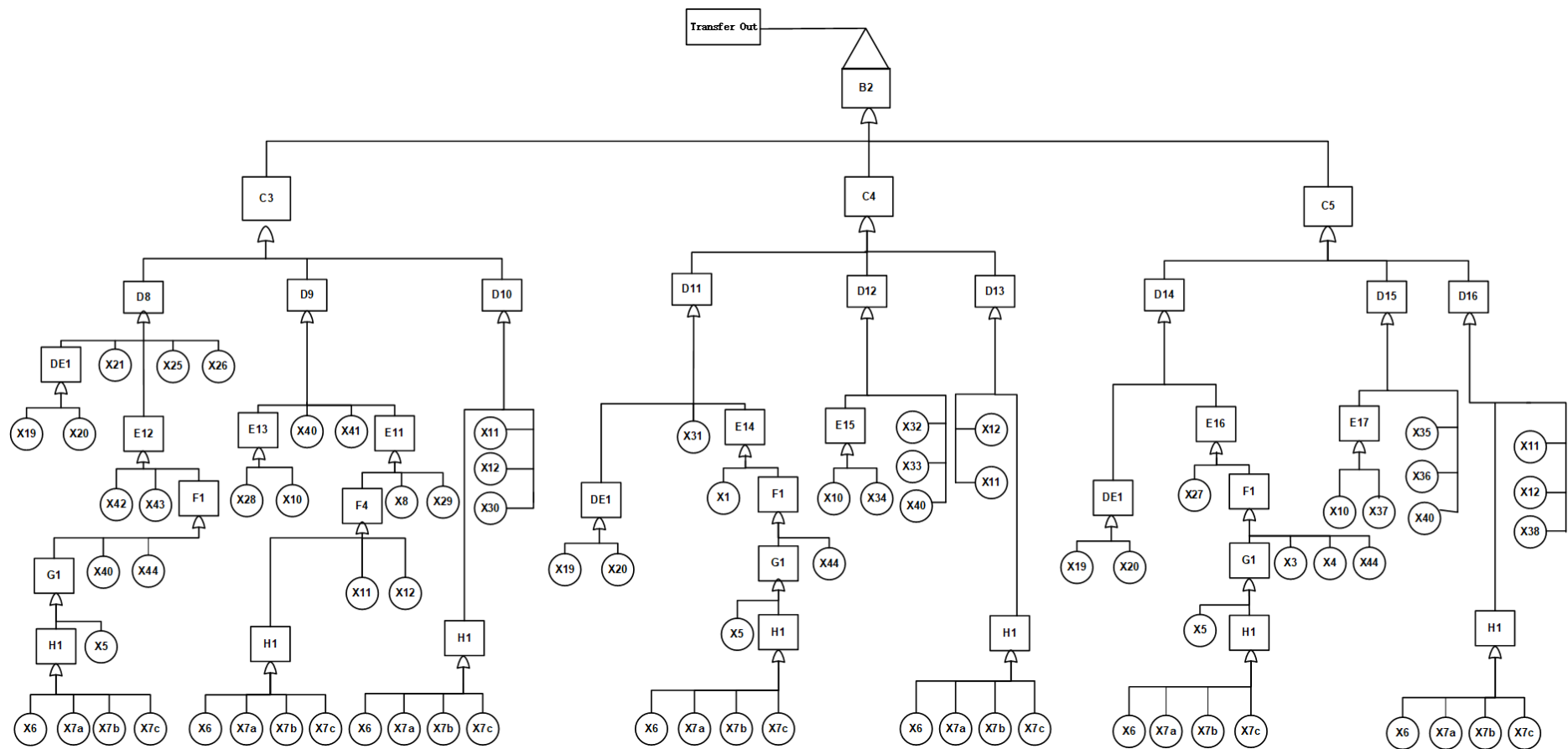


Figure 4 Sub-FT for C₃, C₄, and C₅ drainage assets

Establishing the relative importance of contributing factors

To provide an initial insight into where mitigation measures should be targeted, a procedure is known as Fault Tree Importance Analysis was used to determine the relative importance of the basic contributing factors in causing railway drainage failure (see Figures 3 and 4). The procedure involved determining the minimal cut set of basic contributing factors are described below. A minimal cut set is the smallest group of basic factors that can occur, excluding redundant factors, for the top event to transpire.

Typically, the algebra of sets is used to calculate the minimal cut sets, however, a simplified analysis can be used when the OR gate dominates the structure of an FT, as advocated by Ma *et al.* (31). This simplified analysis focuses only on the cut sets with an AND gate. Using this approach, scrutiny of the fault trees presented in Figures 3-4 yielded 51 minimal cut sets i.e., 51 ways in which basic contributing factors or their combinations can lead to railway track drainage failure.

The minimal cuts sets are as follows:

{X₁}, {X₂}, {X₃}, {X₄}, {X₅}, {X₆}, {X_{7a}}, {X_{7b}}, {X_{7c}}, {X₈}, {X₃,X₄,X₅}, {X₃,X₄,X₆}, {X₃,X₄,X_{7a}}, {X₃,X₄,X_{7b}}, {X₃,X₄,X_{7c}}, {X₉}, {X₁₀}, {X₁₁}, {X₁₂}, {X₁₃}, {X₁₄}, {X₁₅}, {X₁₆}, {X₁₇}, {X₁₈}, {X₁₉}, {X₂₀}, {X₂₁}, {X₂₂}, {X₂₃}, {X₂₄}, {X₂₅}, {X₂₆}, {X₂₇}, {X₂₈}, {X₂₉}, {X₃₀}, {X₃₁}, {X₃₂}, {X₃₃}, {X₃₄}, {X₃₅}, {X₃₆}, {X₃₇}, {X₃₈}, {X₃₉}, {X₄₀}, {X₄₁}, {X₄₂}, {X₄₃}, {X₄₄}

From the above list, it may be seen that the most frequent two are X₃ (train dead load overloading) and X₄ (train live load overloading), with six times, respectively. Also, the second most frequently contributing factors are X₅ (weak soil), X₆ (flooding from surface water due to heavy rainfall), X_{7a} (flooding from rivers), X_{7b} (flooding from sea), and X_{7c} (flooding from reservoirs), each of which occurs twice. This analysis suggests that train overloading will be one of the most likely occurring basic contributing factors followed by weak soil and flooding.

Having established the minimal cut set, the method proposed by Zhao and Wang (58) was used to determine the relative importance of each basic contributing factor. According to Zhao and Wang (58) the relative importance, $I\phi$, of basic contributing factor i (X_i) can be determined using **Equation 2** as follows:

$$I\phi(X_i) = \frac{1}{k} \sum_{j=1}^m \frac{1}{R_j} \quad (2)$$

Where k is the total number of minimal cut sets, m is the total number of minimal cut sets containing basic contributing factor X_i ($i=1, \dots, n$), and R_j is the number of basic contributing factors of the minimal cut set j containing the basic contributing factor X_i .

As an example, consider the basic contributing factor of a train dead load overloading (X_3). From the above, it may be seen that this occurs in six minimal cut sets (i.e., $m=6$). Similarly, $R_1=1$ and $R_2=R_3=R_4=R_5=R_6=3$ and $K=51$.

$$\text{Then } I\phi(X_3) = \frac{1}{51} \sum_{j=1}^6 \frac{1}{R_j} = \frac{1}{51} \left(\frac{1}{1} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3} + \frac{1}{3} \right) = 0.0523$$

Following a similar analysis, it can be shown that

$$\begin{aligned} X_1=X_2=X_8=X_9=X_{10}=X_{11}=X_{12}=X_{13}=X_{14}=X_{15}=X_{16}=X_{17}=X_{18}=X_{19}=X_{20}=X_{21}=X_{22}=X_{23}=X_{24}=X_{25}=X_{26}=X_{27} \\ =X_{28}=X_{29}=X_{30}=X_{31}=X_{32}=X_{33}=X_{34}=X_{35}=X_{36}=X_{37}=X_{38}=X_{39}=X_{40}=X_{41}=X_{42}=X_{43}=X_{44} = 0.0196, \\ X_3=X_4=X_5=X_6=X_{7a}=X_{7b}=X_{7c} = 0.0523 \end{aligned}$$

Accordingly, the five causal contributing factors that have the greatest influence on drainage system failure are X_3 , X_4 , X_5 , X_6 , X_{7a} , X_{7b} , and X_{7c}

Estimation of the Likelihood of Occurrence of Contributing Factors

As described above, FTA uses Boolean algebra to relate failure to basic causal events. Accordingly, the probability of a failure event can be estimated if the probability of occurrence of the basic contributing factor is known. For example, the probability of blocked channel drains and ditches ($P(D_8)$) can be estimated if the probability (P) of the factors contributing to its failure, involving X_{21} , X_{25} , X_{26} , $DE1$, and E_{12} are known (see Table 3 and Figure 4)

Assuming that the probability of occurrence of a basic contributing factor follows a Poisson process, i.e., the basic contributing factors occur in any specific short time period and the contributing factors are independent. Then the probability, $P_{X_i}(x)$ of x occurrences of a basic contributing factor in time t can be calculated using **Equation 3** (4,57).

$$P_{X_i}(x) = \begin{cases} \frac{(\lambda t)^x \exp(-\lambda t)}{x!} \\ 0 \end{cases} \quad (3)$$

Where

$P_{X_i}(x)$: the probability of x occurrences of basic event X_i in a period of time t
 λ : failure rate, the average rate of occurrence of events per time unit
 x : 0.1.2.3..... n occurrence time(s)
 t : time period (e.g. per year)

The failure rate $\lambda(t)$ is defined by **Equation 4** as follows:

$$\lambda(t) = \frac{\text{number of failures per unit time}}{\text{number of components exposed to failure}} \quad (4)$$

From **Equation 4**, the frequency of occurrence of the basic contributing factor, X_i , within a length of track can be written as:

$$\lambda X_i = \frac{f X_i * L h}{L_s} \quad (5)$$

Where

The length of the track is such that the frequency of occurrence of X_i is assumed to be constant along the length i.e. the section of track is termed homogenous.

λX_i : rate of occurrence of basic contributing factor X_i (time(s)/year)
 $f X_i$: frequency of occurrence of basic contributing factor (time(s)/year)
 $L h$: length of the homogeneous section (m)
 L_s : length of the sections exposed to failure (i.e. length of the assessed drainage assets)(m)

The assumption of a Poisson process is not unreasonable since the occurrence of a contributing factor in any specified short time period is likely to confirm with the intended time period e.g., flooding from surface water may occur several times in one year and the occurrences of factors are statistically independent of a disjointed time period (4,57).

Uncertainty estimation

As discussed above the process of determining the likelihood of failure involves assessing the probability of occurrence of the basic contributing factors using the Poisson process. However, the

Poisson process requires the occurrence rate of drainage assets to be specified for the period of analysis. This rate, however, is difficult to quantify for drainage assets, particularly for ageing railways, since the number of historical occurrences is not always known. Further as operational and environmental conditions as are likely to change, the future rates may not match the historical rates on a given section of railway track. For example, increased drainage maintenance on a section of track may reduce the future number of times drains become clogged. Alternatively, a future increase in train loads and speeds may increase the loading on drainage components thereby increasing the occurrence rate. To address such uncertainties, a simulation technique is required which makes use of historical data and expert opinion to provide estimates of the likelihood of failure. MCS was chosen for this purpose since it can be used to model uncertain inputs using a variety of probability distributions (4,11) and it has been widely used for similar applications including those described by Garlic (23) and El-Cheikh and Burrow (20). The output of a Monte Carlo simulation is a range of possible outcomes each with a relative frequency, or likelihood, of occurrence.

Accordingly, MCS was used to evaluate the effect of uncertainty by considering the occurrence rate (λ) as a distribution of potential values each with a probability. The triangular and PERT distributions are commonly used probability distributions for this purpose (15). PERT distribution was chosen since it has smoother tails at either end of the distribution which can better represent uncertainty (15).

CASE STUDIES

Following consultation with Network Rail (NR), the UK's railway infrastructure owner and operator, three sites (i.e. Ardsley Tunnel, Clay Cross Tunnel and Draycott) were selected to demonstrate the use of the developed approach for the analysis of channel drains and ditches. All three sites have similar traffic levels and are considered to be 'high priority mainlines' by NR. These sites were selected based on:

- The availability of ten years of records of historical incidents associated with drainage failure of ballasted railway track. These resulted in frequent flooding events that had substantial consequences (e.g., train delays, unplanned maintenance).
- The presence of channel drains and ditches (C_3), pipes (C_1), catchpits and manholes (C_2).
- The availability of NR's senior drainage engineer to provide an expert opinion about each site.

For each of the three sites, the analysis was conducted over a 200 m length of the homogeneous section of track, concerning the probability of flooding as shown in Figure 4a-c. Accordingly, the assessments could be considered to be IQL II/III (44).

Ardsley Tunnel

Ardsley Tunnel is 206 m long and has 1,207 m of C_3 drainage asset (see Figure 5a). The section is in the middle of a cutting, making it prone to flooding from excessive water dissipating from the top of the cutting when C_3 drainage assets are defective or when they fail. The drains and ditches are adjacent to a wetland area and ponds, which as a result are subject to various basic contributing factors which can cause flooding, for example, scour. Historical data suggests that drainage associated problems are likely to occur, as indicated by the number of times the track has been submerged over the last ten years. For the analysis a homogeneous section after the tunnel gate towards Leeds was chosen.

Clay Cross Tunnel

Clay Cross Tunnel is 1,631 m long with 994 m of channel drains and ditches on either side (see Figure 5b). The C_3 drainage assets are built adjacent to a wetland and ponds.

Draycott

The Draycott site is adjacent to a canal, a highway and dense residential areas (see Figure 5c). The length of C_3 drainage assets on the site is 3219 m on each side. The incident data shows that drainage related problems are likely to occur in the vicinity of the railway track located near to the canal and the highway fly-over.

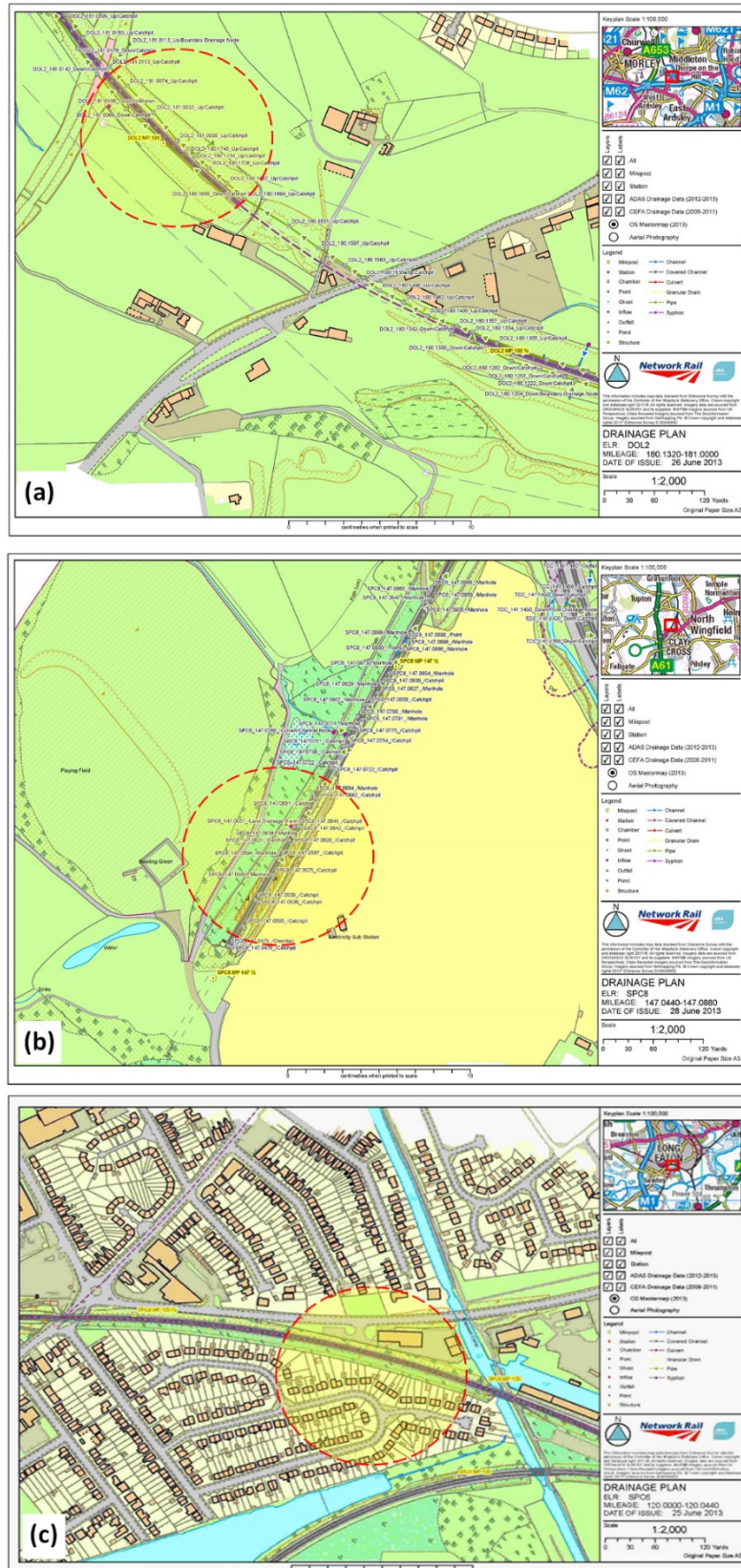


Figure 5 Homogeneous section and map of drainage assets at (a) Ardsley Tunnel, (b) Clay Cross Tunnel, and Draycott (sources, after Network Rail (36,37,38))

Failure probabilities at the selected sites

The analysis of the three sites focused on the basic contributing factors associated with the failure of channel drains and ditches (C_3) and the probability of three intermediate contributing factors namely blockage ($P(D_8)$), collapse ($P(D_9)$) and inadequate capacity ($P(D_{10})$). By inspection of Tables 3 and 4, it can be seen that there are 22 possible basic contributing factors associated with these three intermediate contributing factors. However, an inspection of the available site data and from consultation with NR's senior drainage engineer it was found that only 11 of these basic contributing factors were possible. Two are related to the environment (X_6, X_{7a}), three are associated with land-use (X_{11}, X_{12}, X_{40}), five are related to maintenance ($X_{19}, X_{20}, X_{25}, X_{26}$, and X_{42}) and one is related to components (X_{28}). The estimated frequency of occurrence of each contributing factor and the sources of these data are summarised in Table 4.

The probabilities of failure of the channel drains and ditches at the sites were determined by using the FT-MCS process described above. Firstly, probability distributions were determined for each contributing factor and then these were combined using MCS taking into account the Boolean relationships described by the sub-Fault Tree for channel drains and ditches (see sub-FT C_3 assets in Figure 4). For example, the Boolean algebra for C_3 assets may be written as **Equation 6**:

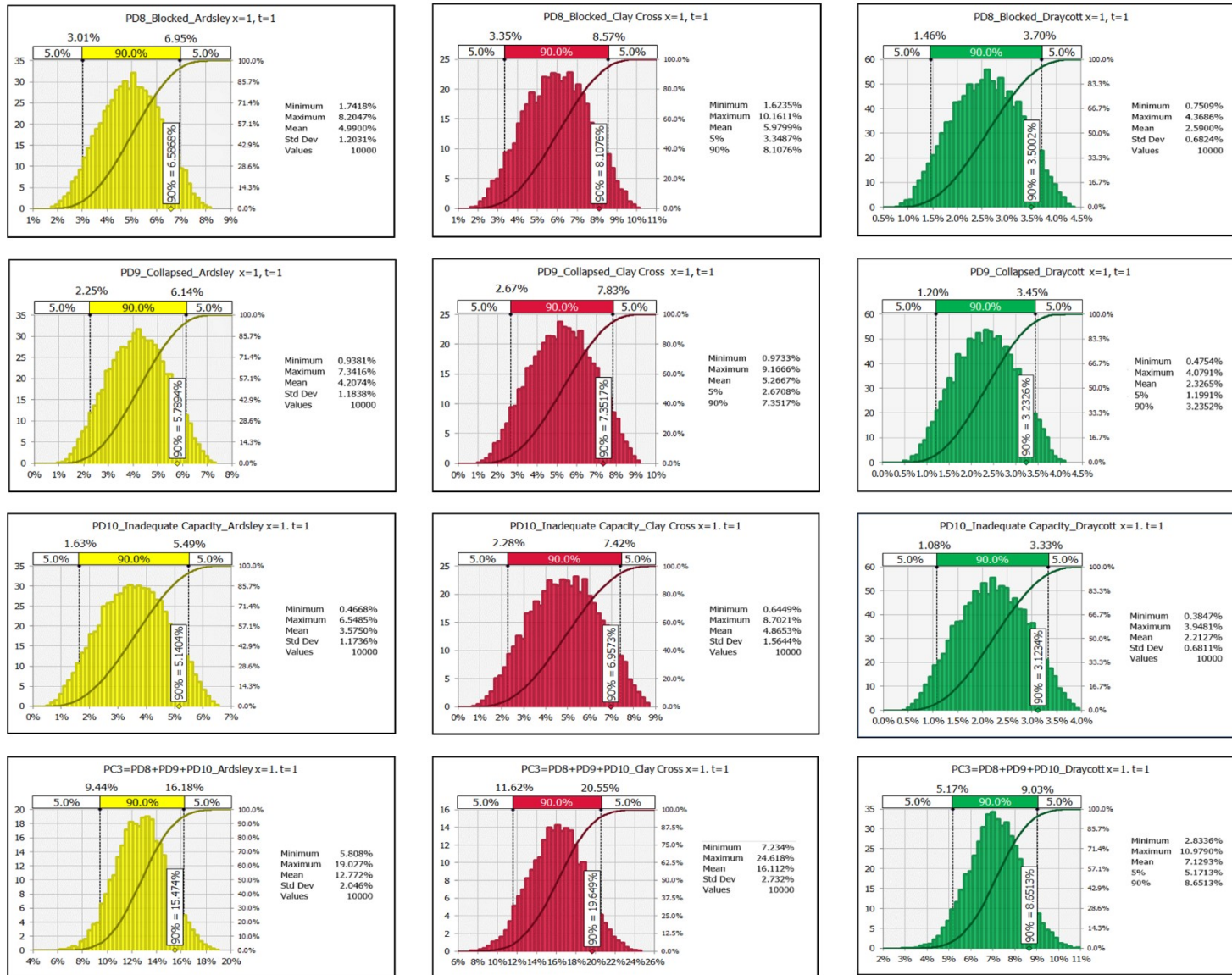
$$P(C_3) = 3.P(X_6) + 3.P(X_{7a}) + 3.P(X_{7c}) + 2.P(X_{11}) + 2.P(X_{12}) + P(X_{19}) + P(X_{20}) + P(X_{25}) + P(X_{26}) + P(X_{28}) + P(X_{29}) + 2.P(X_{40}) + P(X_{42}) + P(X_{43}) \quad (6)$$

Using the above equations (i.e. Equation 3- 6), the probability of occurrence of the contributing factors, failure modes, and failure event (i.e. $P(C_3)$) were quantified. The input data were obtained from historical data (see Table 4). Figure 6a-c shows the resulting probability of occurrence of the three failure modes (i.e. blocked, collapsed and inadequate capacity), both individually and when combined (giving the likelihood of the occurrence of a defective or failed channel drains and ditches). The results for the Ardsley tunnel, with 90% confidence, shows that the probability of blocked failure mode $P(D_{8\ 90})$ is 3.01 - 6.95%, collapse $P(D_9)$ is 2.25-6.14%, inadequate capacity $P(D_{10})$ is 1.63 - 5.49% and defective or failed channel drain and ditches are 9.44 - 16.18% (see Figure 6a). The corresponding values for the Clay Cross tunnel are 3.35 - 8.57%, 2.67 - 7.83%, 2.28 - 7.42% and 11.62 - 20.55% respectively (see Figure 6b). For Draycott, the corresponding probabilities are 1.46 - 3.70% for blocked, 1.20 - 3.45% for collapse, 1.08 - 3.33% for inadequate capacity, and 5.17 - 9.03% for the failure of the channel drains and ditches (see Figure 6c). These results suggest that the focus of maintenance interventions should be on cleaning blockages due to vegetation overgrowth and debris cleanout. The probabilities of defective or failed channel drain and ditches, at the 90% confidence level, are 15.47%, 19.65%, and 8.65% for Ardsley tunnel, Clay Cross tunnel and Draycott respectively (see Figure 6a,b, and c). In all cases, the probability of defective or failed channel drains and ditches were observed to be higher than the value without considering uncertainty. For example, at Clay Cross tunnel the $P(C_3)_{90}$ is 19.65%, whereas the value without considering uncertainty is 16.11% (see Figure 6b).

From the above, it is evident that the likelihood of defective, or failed, channel drains and ditches at Clay Cross Tunnel is higher than at both the Ardsley Tunnel and Draycott sites. It is also apparent that blockages are more likely to occur than collapses and inadequate capacity at all three sites. The likelihood of defective, or failed, assets are also affected by the rate of occurrence of the basic contributing factors at the site. This can be seen from the likelihood values at the Draycott site. While the frequency of flooding at the Draycott site is higher than at the other two sites, the length of channel drains and ditches exposed to failure is the greatest at Draycott and therefore it was found to have the lowest likelihood of failure (see Figure 6a-c).

TABLE 4 Availability and frequency of occurrence of influencing factors at the Ardsley Tunnel, Clay Cross Tunnel, and Draycott sites

Code	Basic Event/ Risk	Ardsley Tunnel					Clay Cross Tunnel					Draycott					Source of Data
		Availability	Frequency (x times in t years)	Three points estimation of frequency			Availability	Frequency (x times in t years)	Three points estimation of frequency			Availability	Frequency (x times in t years)	Three points estimation of frequency			
				Min	Mid	Max			Min	Mid	Max			Min	Mid	Max	
X6	Flooding from surface water	√	0 - 8 in 10	0.0E+00	4.0E-01	8.0E-01	√	0 - 9 in 10	0.0E+00	4.5E-01	9.0E-01	√	0 - 12 in 10	0.0E+00	6.0E-01	1.2E+00	NR record
X7a	Flooding from river	√	1 in 1000 - 1 in 100	1.0E-03	5.5E-03	1.0E-02	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	UK's flood map: Environment Agency (2018)
X7c	Flooding from reservoirs	-					-					√	1 in 1000 - 1 in 100	1.0E-03	5.5E-03	1.0E-02	UK's flood map: Environment Agency (2018)
X11	Change to land use (catchment area)	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	Ordnance Survey (2018)
X12	Changes to drain upstream	√	1 in 100 - 1 in 30	1.0E-02	6.6E-01	1.3E+00	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	Ordnance Survey (2018)
X19	Lack of debris clean out	√	0 - 1 in 10	0.0E+00	5.0E-02	1.0E-01	√	1 in 30- 1 in 10	3.3E-02	6.7E-02	1.0E-01	√	1 in 30- 1 in 10	3.3E-02	6.7E-02	1.0E-01	NR record
X20	Non ballast material infiltration (waste from the train, spillage from the train, fly tipping)	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	-					Ordnance Survey (2018)
X25	Vegetation overgrowth	√	0 - 1 in 10	0.E+00	5.5E+01	1.E+02	√	0 - 1 in 10	0.0E+00	5.0E-02	1.0E-01	√	1 in 30 - 1 in 10	3.3E-02	6.7E-02	1.0E-01	NR record
X26	Spoil tipping	√	1 in 100 - 1 in 30	1.E-02	2.2E-02	3.E-02	-										NR record
X28	Aging channel drains and ditches material	√	0 - 1 in 50	0.E+00	1.0E-02	2.E-02	-					√	1 in 50 - 1 in 30	2.0E-02	2.7E-02	3.3E-02	Spink <i>et al.</i> (2014)
X29	Scour around channel drains and ditches	-					√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	-					Network Rail (2018)
X40	Damage caused by other assets/ 3rd party assets	√	0 - 1 in 10	0.E+00	5.0E-02	1.E-01	√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	-					NR record
X42	Lack of silt clean out (channel drains) or excavate (ditches)	√	1 in 30 - 1 in 10	3.3E-02	6.7E-02	1.0E-01	-					√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	Ordnance Survey (2018)
X43	Damage caused by poor installation	-					-					√	1 in 100 - 1 in 30	1.0E-02	2.2E-02	3.3E-02	NR record



a (Ardsley Tunnel)

b (Clay Cross Tunnel)

c (Draycott)

Figure 6 The range of likelihoods of defective or failed C_3 drainage assets $P(C_3)$ at (a) Ardsley Tunnel, (b) Clay Cross Tunnel and (c) Draycott for the three individual failure modes namely, blocked $P(D_8)$, collapsed $P(D_9)$, and inadequate capacity $P(D_{10})$ and the combined failure $P(C_3)$

To identify the factors that have the most influence on the probability of a failure, a sensitivity analysis was conducted by varying each possible causal factor in turn and keeping all others constant. The results, in the form of tornado graphs (see Figures 7a-c), show that the predominant causal factor for this type of failure across the three selected sites is flooding from surface water (X_6). While the least influential factor for Ardsley Tunnel is non-ballast material infiltration (X_{20}), it is flooding from rivers (X_{7a}) at both Clay Cross Tunnel and Draycott.

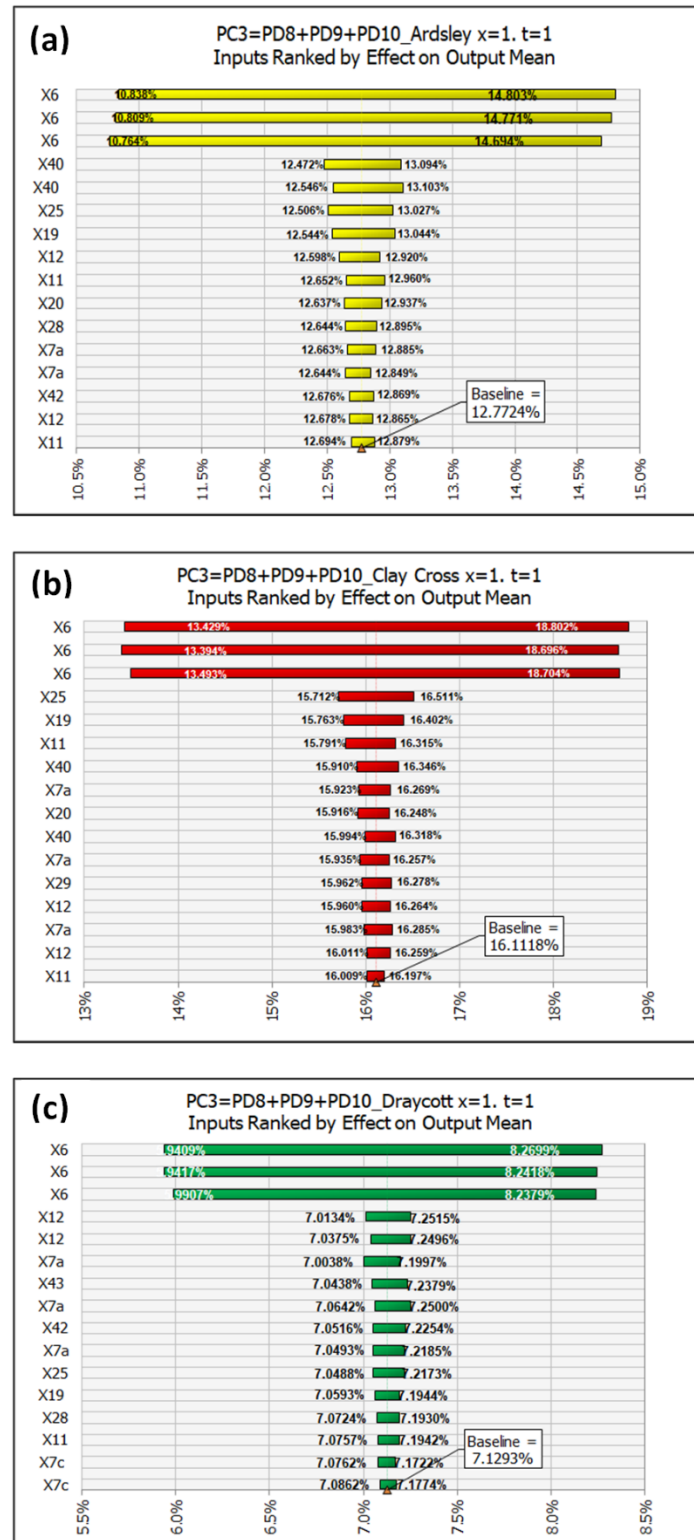


Figure 7 Tornado graph as sensitivity analysis of MCS for (a) Ardsley Tunnel, (b) Clay Cross, and (c) Draycott

CONCLUDING DISCUSSION

This paper proposed a risk-informed approach to assess the probability of failure of drainage assets as an enabler for railway drainage tactical asset management. The approach provides a robust method that enables drainage asset managers to identify, scrutinise and rank the likelihood of the factors that can contribute to drainage failure. This can help the drainage asset manager to select and prioritise, in a rational and transparent manner, appropriate mitigation measures to locations in the railway network at greatest flood risk.

A probabilistic fault tree approach was proposed to identify and interrelate the contributing factors that can lead to railway track drainage failure and by so doing enable the probability of drainage failure to be determined. Monte Carlo Simulation (MCS) was used to quantify the uncertainty associated with the probability of occurrence of these contributing factors and thereby the overall probability of failure of a drainage asset.

Use of Fault Trees

The fault tree approach was chosen because it provides a rational, structured approach to identify and interrelate the factors that can contribute to railway drainage failure. Further, the fault tree structure enables an analysis of the importance of the most influential causes of failure risk based on their position in the structure. The comprehensive list of identified contributing factors identified in the research can be converted into a simple checklist for an initial risk evaluation process.

Fault tree development

The developed fault trees were formulated from a combination of a review of the literature, brainstorming and expert elicitation via a focus group discussion (FGD). The FGD brought together senior drainage experts, risk managers and track bed engineers, all with considerable practical knowledge of railway operations (including track drainage) and provided a platform for the discussion of opinions and the sharing of expertise. Thus it enabled the experts to engage meaningfully in the development of the model. The format of the workshop helped to build consensus among experts through group discussion and helped to avoid bias which might have occurred during individual consultations. As a result, it was possible to identify complex potential faults and incidents that could lead to drainage failure and to better understand the resulting impacts which would not otherwise have been possible to ascertain from the literature alone. An added benefit was that the workshop brought together a variety of experts, not all of who are involved in the day to day management of drainage and who might therefore not otherwise have had such a forum to discuss and debate problems that are better solved collectively. The workshop thereby reinforced collective responsibility and collaboration within the organisation.

This approach, however, is time-consuming and required significant human resource and buy-in from the railway organisation and it, therefore, may not be practicable for every application. To reduce the resources required in developing fault trees for other railways, the developed fault trees could be adapted for other railway environments. However, it needs to be borne in mind that the fault trees were configured with the UK railway operating environment in mind. i.e., a congested and ageing mixed passenger-freight railway network operating in relatively densely populated areas in a temperate climate. Any adaptation therefore of the developed fault trees would need to be done with care.

Failure probabilities

Determining the probability of the failure of drainage assets using the proposed approach involves providing a rate of occurrence of the basic contributing factors identified within the fault tree. For many railways, these rates of occurrence are difficult to quantify due to a paucity of historical data and also because changing operational and environmental conditions can mean that future rates of occurrence may not match those which have occurred in the past. To address this lack of data we proposed the use of a combination of expert opinion, historical data and information available in the literature to determine a plausible range of values for each contributing factor. To deal with uncertainty, MCS was used thereafter to provide a distribution of possible likelihoods of drainage failure.

Other methods could be used to deal with both uncertainty and the use of expert opinion, such as Fuzzy logic. However, the drainage experts within Network Rail who examined the outputs from the analysis of the three case studies found that the MCS outputs produced were easy to understand and that the approach was transparent, even though they were not experts in risk analysis.

To simulate the rate of occurrence of a contributing factor a Poisson's process was used since it is widely used in similar applications. For the three cases studies, the predicted ranges of occurrence of the basic events and the range of predicted drainage failure probabilities were discussed with drainage experts who found the ranges to be plausible. This suggests that the Poisson distribution used was appropriate for the case studies. Nevertheless, it is recommended that any application of the approach described here should consider other distributions, such as bernoulli, binomial, and geometric, as these might result in more appropriate predictions of failure for the application considered. However, these approaches require estimation based on trials or sequences where the first trial probability is known. This data however was not known for the three case studies.

Although the fault tree model has been well received by the UK railway industry, further refinements are desired. In particular, the approach assumed that contributing factors occur independently and therefore dependencies between the failure mechanisms were not established within the fault trees. Consequently, possible interactions between failure modes were not considered.

Risk and Asset Management

The paper suggested, via a framework, how risk management can be incorporated within the three accepted levels of railway asset management, namely strategic, tactical and operational. **The approach advocated in this paper for the assessment of drainage assets is designed to support tactical asset management decision making regarding the performance, investment and implementation of works programmes. As far as performance is concerned, the approach enables the failure likelihood of sections of the railway network to be quantified and changes monitored over time. The approach also facilitates the assessment of drainage asset failure in the medium term and allows for the identification and analysis of critical drainage assets, associated failure modes and the identification of sections of railway track at high likelihood of drainage failure. The drainage failure likelihood of individual sections of railway track could also be amalgamated for an entire network, using a strategic level asset management approach, to yield a measure of overall railway drainage network performance. By quantifying the performance of sections of track, investment in drainage maintenance and renewal can be target to those sections with the greatest failure probability and works programmes designed accordingly. Such an approach would also aid in making a business case for investing in predictive and preventive asset management regimes. However, in order to be effective, the strategies designed to improve the reliability and resilience of the railway drainage assets need to account for uncertainties associated with predicting the performance and condition of the asset. Furthermore, potentially expensive inspection and monitoring regimes could also be targeted towards those sections of track within a railway network with the greatest failure likelihood. For example, results from the case studies suggest that surface flooding due to heavy rainfall is the major causal factor for drainage failure across all the three sites (see Table 4 and Figures 7a-c). The analysis showed that drainage blockages are more likely to occur than collapse or inadequate capacity. Consequently, maintenance interventions at all three sites should prioritise clearing blockages due to vegetation overgrowth and debris cleanout. Further, considering the relatively higher probability of flooding from rivers, weather monitoring and flood defence schemes could be prioritised for Clay Cross Tunnel and Draycott sites instead of Ardsley Tunnel.**

As discussed above, data plays an essential role in the proposed approach since it is used to estimate the failure rate of the identified risk events and these governs the procedure for probability estimation. Integrating the proposed approach within a tactical level asset management system could enable data stored within the databases of such systems to be easily accessed and interrogated. The customisation of the databases of typical tactical level asset management systems should include provision for data relating to the climate, historical flood events and failure mechanisms in addition to the more typical

data associated with inventory, component condition, maintenance history and track usage. Some of this additional data may need to be provided by expert opinion using the approaches discussed above. This can present a challenge for organisations not used to risk-informed asset management approaches. In this research, this was overcome through the FGD setting that brought together senior drainage experts, risk managers and track bed engineers to discuss the issues and determine the likelihood of occurrence of events.

Data used for tactical asset management can be regarded as being at IQL II-III and can be categorical i.e. summary data collected for sections of railway track between 20 m to 1 km in length (44). For the case studies, 200 m lengths of railway track were assessed because this is the length Network Rail uses for maintenance planning purposes and therefore there would be sufficient data being available for the assessment. The actual sections of track considered at the three sites were chosen so that the impacts of failure of any drainage assets could be considered to be constant, from a tactical asset management point of view, over the section. An asset management system configured to deal with 200 m sections of railway track could thereby be used to prioritise drainage maintenance interventions based on the likelihood of drainage risk failure for each 200 m section of railway track considered within the asset management system.

Although this paper has developed a FTA-MCS approach to identify the factors which can cause drainage failure and quantify the contribution of these factors to failure probability under uncertainty, a comprehensive analysis of drainage failure risk also requires consideration of the potential impacts of failure (see Equation 1). Potential impacts which need to be considered include those associated with unplanned track maintenance/repair, third party damage, contractual issues, the environment, financing, operations (particularly where traffic has or is forecast to increase), reputation, safety and service provision [56]. Such an approach will enable economic appraisal using a whole life cycle asset management to inform inspection regimes, prioritise preventive maintenance of drainage assets in sensitive areas of greatest failure risk and to identify cost-effective strategies to reduce risk (60). The latter may include, for example, the use of more initially expensive designs such as slab track but which have lower life cycle drainage failure associated maintenance cost risks (56).

ACKNOWLEDGMENTS

The authors would like to acknowledge with gratitude the DIKTI/DGRSTHE (Directorate General of Resources for Science, Technology and Higher Education) scholarship scheme provided by the Indonesian government which supported this research. The Department of Civil Engineering at the University of Birmingham, UK is also thanked for facilitating the research. The assistance with the development of the Fault trees and the provision of data for the case studies by Network Rail UK (drainage division) is gratefully acknowledged.

AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: Kristianto Usman, Michael Peter Nicholas Burrow, Gurmel Singh Ghataora; data collection: Kristianto Usman, Michael Peter Nicholas Burrow, Gurmel Singh Ghataora; analysis and interpretation of results: Kristianto Usman, Michael Peter Nicholas Burrow, Manu Sasidharan; draft manuscript preparation: Kristianto Usman, Michael Peter Nicholas Burrow, Manu Sasidharan. All authors reviewed the results and approved the final version of the manuscript.

REFERENCES

1. Ana E, Bauwens W. Modeling the structural deterioration of urban drainage pipes: the state-of-the-art in statistical methods. *Urban Water Journal*. 2010;7(1):47-59.
2. An M, Huang S, Baker C. Railway risk assessment-the fuzzy reasoning approach and fuzzy analytic hierarchy process approaches: a case study of shunting at waterloo depot. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of rail and rapid transit*. 2007;221(3):365-83.

3. ASCE. *Standard Guidelines for the Design, Installation, and Operation and Maintenance of Urban Subsurface Drainage*: American Society of Civil Engineers; 2006.
4. Ayyub BM, McCuen RH. *Probability, statistics, and reliability for engineers and scientists*: CRC press; 2016.
5. Baah K, Dubey B, Harvey R, McBean E. A risk-based approach to sanitary sewer pipe asset management. *Science of the Total Environment*. 2015; 505:1011-7.
6. Balsells M, Becue V, Barroca B, sur Marne C, Diab FY, Serre D. Flood resilient city design: a review of existing methods and tools. *Land Use Planning and Risk-Informed Decision Making*. 2014:279.
7. Barnett SJA. *The use of a risk-based approach to identify the uncertainties associated with flooding of highway drainage infrastructure*. PhD Thesis. University of Birmingham; 2016.
8. Beard AN. Tunnel safety, risk assessment and decision-making. *Tunnelling and Underground Space Technology*. 2010;25(1):91-4.
9. Berrado A, El-Koursi E, Cherkaoui A, Khaddour M. A framework for risk management in railway sector: application to road-rail level crossings. *Open transportation Journal*, Bentham Open, 2010, 19p. hal-00542424.
10. BSI (2008) Publicly Available Specification (PAS) *PASS 55-2008. Asset Management, Specification for the optimized management of physical assets*. British Standards Institution, UK, 2008.
11. BSI Standards Publication. *BS EN 31010:2010: Risk Management - Risk Assessment Techniques*. British Standards, London, 2010.
12. Chiachío J, Chiachío M, Prescott D, Andrews J. A reliability-based prognostics framework for railway track management. *Annual Conference of the Prognostics and Health Management Society*. 2017.
13. Coulthard T, Frostick L. The Hull floods of 2007: implications for the governance and management of urban drainage systems. *Journal of Flood Risk Management*. 2010;3(3):223-31.
14. Crapper M, Fell M, Gammoh I. Earthworks risk assessment on a heritage railway. *Proceedings of the Institution of Civil Engineers-Geotechnical Engineering*. 2014;167(4):344-56.
15. Cretu O, Stewart RB, Berends T. *Risk management for design and construction*: John Wiley & Sons; 2011.
16. DfT (Department for Transport). *Transport resilience review: a review of the resilience of the transport network to extreme weather events*. Her Majesty's Stationery Office, London. UK. 2014.
17. DfT (Department for Transport). *Highway Infrastructure Asset Management Guidance Document*. Her Majesty's Stationery Office, London. UK. 2013.
18. Environment Agency. Flood risk from rivers and reservoirs at Ardsley Tunnel, Clay Cross Tunnel, and Draycott. 2018. Available at: <https://flood-warning-information.service.gov.uk/long-term-flood-risk/map> (Accessed: 15 June 2018).
19. El-Cheikh, M., Al Sheikh, D., & Burrow, M. P. N. Project Appraisal of Rail Projects Using Fuzzy Sets Theory. *The International Journal of Railway Technology*. 2013; Volume 2(Issue -1), pp 39-62.
20. El-Cheikh M, Burrow MP. Uncertainties in forecasting maintenance costs for asset management: Application to an aging canal system. *ASCE-ASME journal of risk and uncertainty in engineering systems, part A: civil engineering*. 2017;3(1):04016014.
21. Flammini F, Gaglione A, Mazzocca N, Pragliola C, editors. Quantitative security risk assessment and management for railway transportation infrastructures. *International Workshop on Critical Information Infrastructures Security*; 2008: Springer.
22. Flyvbjerg B. Cost overruns and demand shortfalls in urban rail and other infrastructure. *Transportation Planning and Technology*. 2007;30(1):9-30.
23. Garlick A. *Estimating Risk: A Management Approach*: Taylor & Francis; 2017.
24. IRM. *A risk management standard*. AIRMIC (The Association of Insurance and Risk Managers), ALARM (The National Forum for Risk Management in the Public Sector), IRM (The Institute of Risk Management). 2002.

25. Kalantari Z, Folkesson L. Road drainage in Sweden: current practice and suggestions for adaptation to climate change. *Journal of Infrastructure Systems*. 2013;19(2):147-56.
26. Kandilioti G, Makropoulos C. Preliminary flood risk assessment: the case of Athens. *Natural hazards*. 2012;61(2):441-68.
27. Ko CK, Chowdhury R, Flentje P. Hazard and risk assessment of rainfall-induced landsliding along a railway line. *Quarterly journal of engineering geology and hydrogeology*. 2005;38(2):197-213.
28. Li D, Hyslip J, Sussmann T, Chrismer S. *Railway geotechnics*: CRC Press; 2016.
29. Limnios N. *Fault trees*: John Wiley & Sons; 2013.
30. Liu X, Saat MR, Barkan CPL. Analysis of Causes of Major Train Derailment and Their Effect on Accident Rates. *Transportation Research Record*. 2012;2289(1):154-63.
31. Ma J, Bai Y, Shen J, Zhou F. Examining the Impact of Adverse Weather on Urban Rail Transit Facilities on the Basis of Fault Tree Analysis and Fuzzy Synthetic Evaluation. *Journal of Transportation Engineering*. 2014;140(3):04013011.
32. McBain W, Wilkes D, Retter M. *Flood resilience and resistance for critical infrastructure*: CIRIA; 2010.
33. Merz B, Hall J, Disse M, Schumann A. Fluvial flood risk management in a changing world. *Natural Hazards and Earth System Sciences*. 2010.
34. NAMS (New Zealand Asset Management Support). *International Infrastructure Management Manual*. Institute of Asset Management. London, U.K. (UK edition). 2011.
35. Network Rail. *NR/L3/CIV/005: Railway Drainage Systems Manual*. 2010.
36. Network Rail. Map of drainage assets at Ardsley Tunnel site. Network Rail, York Office. 2013a.
37. Network Rail. Map of drainage assets at Clay Cross Tunnel site. Network Rail, York Office. 2013b.
38. Network Rail. Map of drainage assets at Draycott site. Network Rail, York Office. 2013c.
39. Network Rail. Drainage of Railway Ballasted Track: Minutes of meeting-drainage division, 3rd July 2017, Baskerville House, Birmingham. 2017.
40. Network Rail. Draft NR/L2/CIV/005 *Module 4: Drainage Inspections*. 2018.
41. Okada K, Sugiyama T. A risk estimation method of railway embankment collapse due to heavy rainfall. *Structural Safety*. 1994;14(1):131-50.
42. Ordnance Survey. Map of Ardsley Tunnel, Clay Cross Tunnel, and Draycott. Edina Digimap. 2018a. Available at: <https://digimap.edina.ac.uk/> (Accessed: 23 August 2018).
43. Palisade Corporation. *@Risk*. New York, USA: Palisade Corporation. 2017
44. Patterson, W.D.O and Scullion, T. *Information systems for road management: draft guidelines on system design and data issues*. Infrastructure and Urban Development Department Report INU 77. Washington DC: The World Bank. 1990.
45. Pandey M. *Engineering and Sustainable Development: Fault Tree Analysis*. University of Waterloo, Waterloo. 2005.
46. Penning-Rowsell E, Priest S, Parker D, Morris J, Tunstall S, Viavattene C, et al. *Flood and coastal erosion risk management: a manual for economic appraisal*: Routledge; 2014.
47. Ptilakis K, Alexoudi M, Argyroudis S, Monge O, Martin C. Earthquake assessment of Lifelines. *Special Issue, Bulletin of Earthquake Engineering* DOI. 2006;10.
48. Robinson R, Danielson U, Snaith MS. *Road maintenance management: concepts and systems*: Macmillan International Higher Education; 1998.
49. Rodríguez JP, McIntyre N, Díaz-Granados M, Maksimović Č. A database and model to support proactive management of sediment-related sewer blockages. *Water research*. 2012;46(15):4571-86.
50. Sánchez M. Security risk assessments in public transport networks. *Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit*. 2011;225(4):417-24.
51. Sihota, M. The Drainage System, Overview of Current Status, Consequences and Interfaces.” Track Engineering Conference, 30 June 2016. 2016, Available at: https://www.thepwi.org/technical_hub/presentations_for_tech_hub/160630_nr_track_eng_summer_conf/03_160630_nr_track_eng_summer_conf_mona_sihota

52. Spink T, Duncan I, Lawrance A, Todd A. *Transport infrastructure drainage: condition appraisal and remedial treatment*. CIRIA, London. 2014.
53. Tennakoon N, Indraratna B, Rujikiatkamjorn C, Nimbalkar S. Assessment of ballast fouling and its implications on track drainage. In G. A. Narsilio, A. Arulrajah & J. Kodikara (Eds.), *11th Australia - New Zealand Conference on Geomechanics: Ground Engineering in a Changing World*. ANZ Geomechanics.2012. pp. 421-426.
54. Tran D, Ng A, Mcmanus K, Burn S. Prediction models for serviceability deterioration of stormwater pipes. *Structure and Infrastructure Engineering*. 2008;4(4):287-95.
55. Usman K, Burrow M, Ghataora G. Fault Tree for Poor Drainage Mechanisms of Railway Ballasted Track. *Conference: Railway Engineering*; 2017.
56. Usman K. *The development of a risk-informed framework for the appraisal of drainage maintenance of ballasted railway track*, PhD Thesis. University of Birmingham. 2020
57. Ten Veldhuis JA, Clemens FH, van Gelder PH. Quantitative fault tree analysis for urban water infrastructure flooding. *Structure and Infrastructure Engineering*. 2011;7(11):809-21.
58. Zhao N-N, Wang Y-q. A fault tree analysis of a typical lightning strike on aircraft. *ICTIS 2011: Multimodal Approach to Sustained Transportation System Development: Information, Technology, Implementation*. 2011. p. 2024-31.
59. Zhang Y-P, Xu Z-J, Su H-S. Risk assessment on railway signal system based on fuzzy-fmecca method. *Sensors & Transducers*. 2013;156(9):203.
60. Sasidharan M, Burrow MPN, Ghataora GS. A whole life cycle approach under uncertainty for economically justifiable ballasted railway track maintenance, *Research in Transport Economics*. 2020; 80